A4. This question is about nuclear binding energy.

The table below gives the mass defect per nucleon of deuterium $\left({}^{2}_{1}\text{H}\right)$ and helium-4 $\left({}^{4}_{2}\text{He}\right)$.

	Mass defect per nucleon / *u*
${}^{2}_{1}\text{H}$	0.00120
${}^{4}_{2}\text{He}$	0.00760

(a) Explain the term *mass defect*. *[2]*

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(b) Calculate the energy, in joule, that is released when two deuterium nuclei fuse to form a helium-4 nucleus. *[4]*

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(Question B2 continued)

Part 2 Radioactive decay

(a) Carbon-14 is a radioactive isotope with a half-life of 5500 years. It is produced in the atmosphere by neutron bombardment of nitrogen. The equation for this reaction is

$$^{14}_{7}\text{N} + ^{1}_{0}\text{n} \rightarrow ^{14}_{6}\text{C} + \text{X}.$$

(i) Explain what are meant by *isotopes*. *[1]*

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(ii) Define the term *radioactive half-life*. *[1]*

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(iii) Identify the particle X. *[1]*

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(b) Living trees contain atoms of carbon-14. The activity per gram of carbon from a living tree is higher than that per gram of carbon-14 from burnt wood (charcoal) found at an ancient campsite.

(i) A living tree continuously takes in carbon dioxide from the atmosphere. Suggest why the activity of the carbon from the charcoal is less than that of the living wood. *[3]*

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(ii) Each gram of a living tree contains approximately 1×10^{-12} g of the isotope carbon-14. Deduce that each gram of carbon in living wood contains approximately 4×10^{10} atoms of carbon-14. *[2]*

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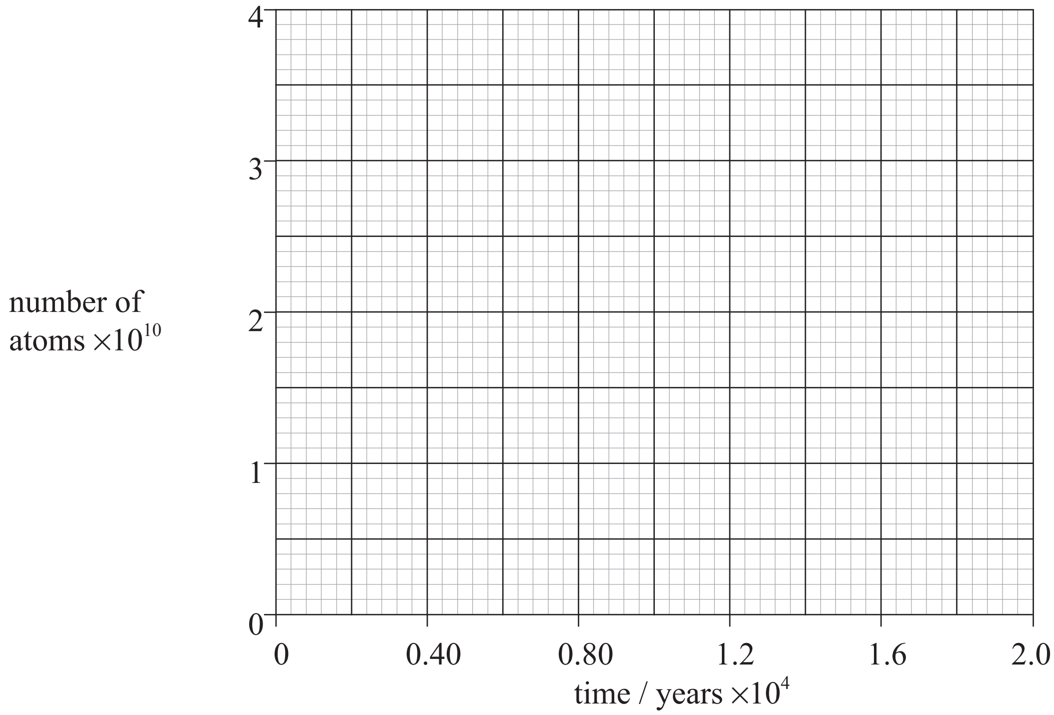
(This question continues on the following page)

(Question B2, part 2 continued)

(c) On the grid below, draw a graph to show the variation with time of the number of carbon-14 atoms in one gram of wood from a tree. Your graph should indicate the number of atoms for a period of 1.8×10^4 years after the tree has died. (Half-life of carbon-14 = 5500 years) *[3]*



(d) The activity of a radioactive sample is proportional to the number of atoms in the sample. The activity per gram of carbon from a living tree is 9.6 disintegrations per minute. The activity per gram of carbon in burnt wood found at the ancient campsite is 1.9 disintegrations per minute.

(i) Estimate the number of atoms of carbon-14 in the burnt wood. *[1]*

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(ii) From the graph you have drawn in (c), estimate the age of the burnt wood. *[1]*

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B2. This question is about nuclear energy.

(a) Define *nuclear binding energy*. *[2]*

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(b) A neutron collides with a nucleus of uranium-235 and the following reaction takes place.

$$^{235}_{92}\text{U} + ^{1}_{0}\text{n} \rightarrow ^{96}_{37}\text{Rb} + ^{138}_{55}\text{Cs} + 2\,^{1}_{0}\text{n}$$

State the name of this type of reaction. *[1]*

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(c) The mass of nuclei can be expressed in terms of unified mass units (u).

(i) Define the term *unified mass unit*. *[1]*

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(ii) Using the data below, calculate the energy, in MeV, that is released in the reaction. *[4]*

$$\text{mass of } ^{235}_{92}\text{U} = 235.0439\,u$$
$$\text{mass of } ^{96}_{37}\text{Rb} = 95.9342\,u$$
$$\text{mass of } ^{138}_{55}\text{Cs} = 137.9112\,u$$
$$\text{mass of } ^{1}_{0}\text{n} = 1.0087\,u$$

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(This question continues on the following page)

(Question B2 continued)

(d) Explain the importance of the two neutrons produced in the reaction. *[2]*

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(e) Each neutron accounts for about 2 MeV of the energy released in the reaction. Suggest what accounts for the rest of the energy released. *[2]*

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~~(f) The reaction in (b) is more likely to take place if the colliding neutron has an energy of about 0.1 eV. In certain types of nuclear reactors in which this reaction might take place, the neutrons produced have their energy reduced by collisions with nuclei of graphite (^{12}C). The law of conservation of momentum can be used to estimate the number of collisions required to reduce the energy of the neutrons to 0.1 eV.~~

~~State the law of conservation of momentum.~~ ~~*[2]*~~

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~~(g) A neutron has a kinetic energy of 2.00 MeV. Deduce that the speed of the neutron is 1.95×10^7 m s^{-1}.~~ ~~*[2]*~~

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~~*(This question continues on the following page)*~~

(Question B1, continued)

Part 2 Nuclear decay

(a) State the nature of an α-particle. *[1]*

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(b) In the Rutherford-Geiger-Marsden experiment to investigate the structure of the atom, α-particles were directed towards a gold foil. Explain why α-particles, rather than electrons, were used in this experiment. *[2]*

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(c) Uranium-238 $\left({}^{238}_{92}\mathrm{U}\right)$ undergoes α-decay to form thorium (Th). The half-life of uranium ${}^{238}_{92}\mathrm{U}$ is 4.5×10^{9} years.

(i) Define *half-life*. *[2]*

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(ii) Write down the nuclear equation for the α-decay of uranium to thorium. *[2]*

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(d) Thorium is radioactive and further decays occur, eventually giving lead which is stable. These further decays all occur within a time that is short compared to the half-life of ${}^{238}_{92}\mathrm{U}$. In a sample of rocks the ratio of the number of uranium atoms to the number of lead atoms is $\frac{1}{7}$.

(i) Estimate the age of the rocks assuming that no lead was initially present in the rocks. *[2]*

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(ii) State **one** further assumption that is made in this estimate. *[1]*

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(Question B2 continued)

Part 2 Radioactive decay

(a) The nucleon number (mass number) of a stable isotope of argon is 36 and of a radioactive isotope of argon is 39.

(i) State what is meant by a *nucleon*. *[1]*

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(ii) Explain, in terms of the number of nucleons and the forces between them, why argon-36 is stable and argon-39 is radioactive. *[4]*

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(b) A particular nucleus of argon-39 undergoes the decay shown by the nuclear reaction equation below.

$$^{39}_{18}\text{Ar} \rightarrow \text{K} + \beta^{-}$$

(i) State the proton (atomic) number and the nucleon (mass) number of the potassium (K) nucleus. *[2]*

Proton number: . . . .

Nucleon number: . . . .

(ii) Use the following data to determine the maximum energy, in J, of the β^{-} particle in the decay of a sample of argon-39. *[3]*

Mass of argon-39 nucleus $= 38.96431\,\text{u}$
Mass of K nucleus $= 38.96370\,\text{u}$

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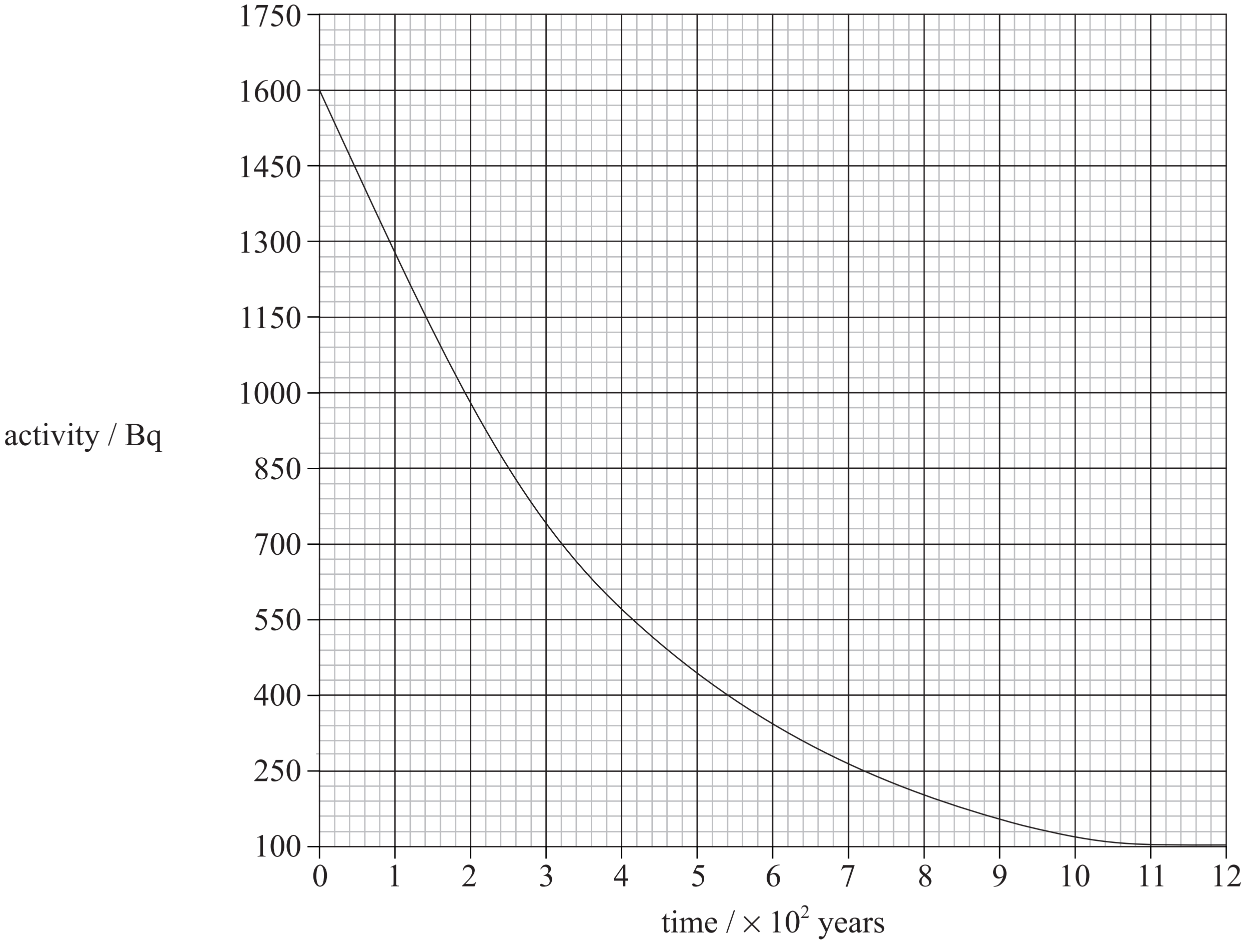
(This question continues on the following page)

(Question B2, part 2 continued)

(c) The graph below shows the variation with time t of the activity A of a sample of argon-39.



Use the graph to determine the half-life of argon-39. Explain your reasoning. *[2]*

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(Question B2, part 1 continued)

(d) The engine that drives the conveyor belt has an efficiency of 40 %. Calculate the input power to the engine. *[2]*

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Part 2 Nuclear reaction

(a) State the meaning of the terms

(i) nuclide *[2]*

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(ii) isotope *[1]*

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(b) A nucleus of ${}^{24}_{11}\text{Na}$ undergoes radioactive decay to the stable nucleus ${}^{24}_{12}\text{Mg}$.

(i) Identify this type of radioactive decay. *[1]*

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(ii) Use the data below to determine the rest mass in atomic mass unit of the particle emitted in the decay of ${}^{24}_{11}\text{Na}$. *[3]*

rest mass of ${}^{24}_{11}\text{Na} = 23.99096u$

rest mass of ${}^{24}_{12}\text{Mg} = 23.98504u$

energy released in decay $= 5.002160$ MeV

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(This question continues on the following page)

(Question B2 part 2 continued)

(c) The isotope sodium-24 is radioactive but the isotope sodium-23 is stable. Suggest which of these isotopes has the greater nuclear binding energy. *[2]*

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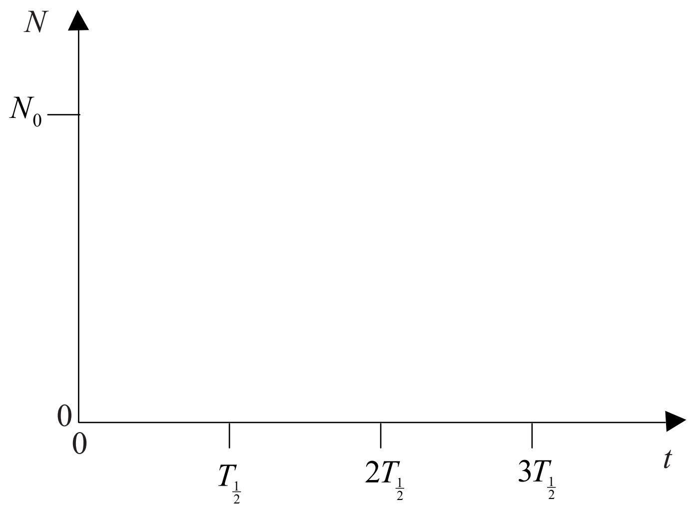
(d) At time $t = 0$, a sample of sodium-24 contains N_0 atoms of sodium-24. The half-life of sodium-24 is $T_{\frac{1}{2}}$.

(i) Using the axes below, draw a sketch graph to show the variation with time *t* of the number *N* of sodium-24 atoms in the sample. *[2]*



(ii) State how the rate at which the sample is decaying at any time *t* can be found from your sketch graph. *[1]*

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(Question B3 continued)

Part 2 Nuclear decay

(a) (i) Describe the phenomenon of natural radioactive decay. *[3]*

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(ii) Ionizing radiation is emitted during radioactive decay. Explain what is meant by the term ionizing. *[2]*

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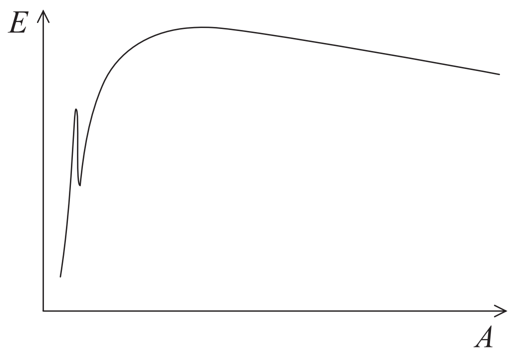
(b) The sketch graph below shows the variation with mass number (nucleon number) A of the binding energy per nucleon E of nuclei.



One possible nuclear reaction that occurs when uranium-235 is bombarded by a neutron to form xenon-142 and strontium-90 is represented as

$$^{235}_{92}\text{U} + ^{1}_{0}\text{n} \rightarrow ^{142}_{54}\text{Xe} + ^{90}_{38}\text{Sr} + 4^{1}_{0}\text{n}.$$

(i) Identify the type of nuclear reaction represented above. *[1]*

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(ii) On the sketch graph above, identify with their symbols the approximate positions of the uranium (U), the xenon (Xe) and the strontium (Sr) nuclei. *[2]*

(This question continues on the following page)

(Question B3, part 2 continued)

(iii) Data for the binding energies of xenon-142 and strontium-90 are given below.

isotope	binding energy / MeV
xenon-142	1189
strontium-90	784.8

The total energy released during the reaction is 187.9 MeV. Determine the binding energy per nucleon of uranium-235. *[3]*

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(iv) State why binding energy of the neutrons formed in the reaction is not quoted. *[1]*

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(Question B1 continued)

Part 2 Nuclear reactions

(a) (i) State what is meant by radioactive decay. *[2]*

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(ii) Radioactive decay is said to be a random process. State what is meant by random decay. *[2]*

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(b) In 1919, Rutherford was investigating the bombardment of nitrogen by α-particles. He discovered that, in the interaction between an α-particle and a nitrogen nucleus, the nitrogen nucleus was transformed into an oxygen nucleus with the emission of a proton.

(i) Complete the nuclear reaction equation for this transformation. *[2]*

$$^{14}_{7}\mathrm{N} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{\dots\dots}_{\dots\dots}\mathrm{O} + {}^{\dots\dots}_{\dots\dots}\mathrm{p}$$

(ii) The rest masses of the particles shown in the reaction equation are given in the table below.

particle	**rest mass / *u***
He	4.00260
N	14.00307
O	16.99913
p	1.00783

Calculate the minimum energy, in MeV, of an α-particle required to cause this transformation to occur. Explain your answer. *[4]*

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(Question B2 continued)

Part 2 Radioactivity

(a) Nuclei of the carbon isotope, C-14, are continuously produced in the atmosphere by the collision of neutrons with nuclei of nitrogen N-14.

(i) Define the term *isotope*. *[1]*

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(ii) State the nuclear reaction equation for the production of a nucleus of C-14 (proton (atomic) number of carbon = 6, proton (atomic) number of nitrogen = 7). *[2]*

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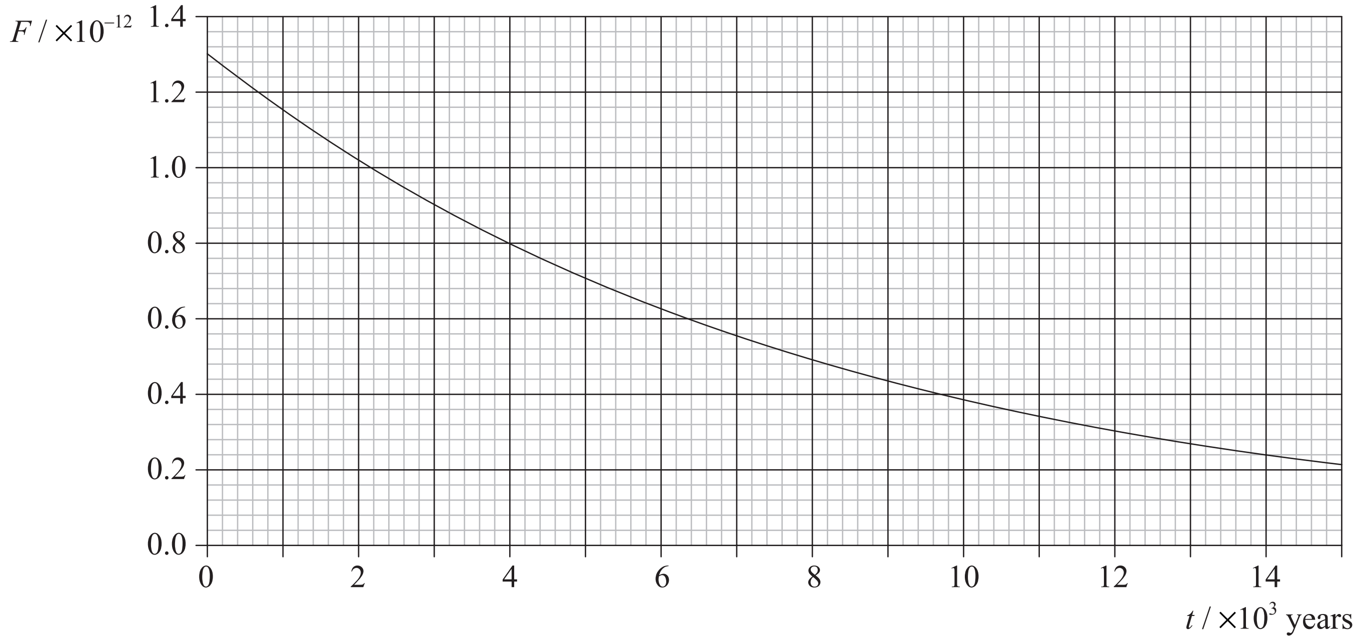
(This question continues on the following page)

(Question B2, part 2 continued)

(b) In a living animal the fraction $F = \frac{\text{number of } {}^{14}_{6}\text{C nuclei}}{\text{number of } {}^{12}_{6}\text{C nuclei}}$ is constant due to the replacement of carbon in the bone.

The graph shows the variation with time t (since death) of the fraction F in the bone of a dead animal.



Explain why the fraction F does not stay constant in the bone of a dead animal. *[2]*

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(This question continues on the following page)

(Question B2, part 2 continued)

(c) Use the graph in (b) to determine the

(i) value of the fraction F for the bone of an animal whilst it was alive. *[1]*

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(ii) half-life of carbon C-14. *[2]*

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(d) Estimate the age of a bone for which $F = 6.0 \times 10^{-13}$. *[2]*

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(e) Suggest why a graph of F versus t is inappropriate for finding the age of a dinosaur bone. *[2]*

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